SHEP/0415

Type II Leptogenesis and the Neutrino Mass Scale

S. Antusch[1], S. F. King[2]

Department of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, U.K.

Abstract

We discuss the effect of the neutrino mass scale on baryogenesis via the out-of-equilibrium decay of the lightest right-handed (s)neutrinos in type II see-saw models. We calculate the type II contributions to the decay asymmetries for minimal scenarios based on the Standard Model and on the Minimal Supersymmetric Standard Model, where the additional direct mass term for the neutrinos arises from a Higgs triplet vacuum expectation value. The result in the supersymmetric case is new and we correct the previous result in the scenario based on the Standard Model. We confirm and generalize our results by calculating the decay asymmetries in an effective approach, which is independent of the realization of the type II contribution. We derive a general upper bound on the decay asymmetry in type II see-saw models and find that it increases with the neutrino mass scale, in sharp contrast to the type I case which leads to an upper bound of about 0.1 eV on the neutrino mass scale. We find a lower bound on the mass of the lightest right-handed neutrino, significantly below the corresponding type I bound for partially degenerate neutrinos. This lower bound decreases with increasing neutrino mass scale, making leptogenesis more consistent with the gravitino constraints in supersymmetric models.

[1]E-mail: `santusch@hep.phys.soton.ac.uk`

[2]E-mail: `sfk@hep.phys.soton.ac.uk`

1 Introduction

Leptogenesis [1] is one of the most attractive mechanisms for explaining the observed baryon asymmetry of the universe, $n_{\mathrm{B}}/n_\gamma = (6.5^{+0.4}_{-0.8}) \cdot 10^{-10}$ [2]. In the type I see-saw scenario [3], where the asymmetry is generated via the out-of-equilibrium decay of the same heavy right-handed neutrinos which are involved in generating neutrino masses, it has been studied intensively. In models with a left-right symmetric particle content like minimal left-right symmetric models, Pati-Salam models or Grand Unified Theories (GUTs) based on SO(10), the type I see-saw mechanism is typically generalized to a type II see-saw (see e.g. [4]), where an additional direct mass term $m_{\mathrm{LL}}^{\mathrm{II}}$ for the light neutrinos is present. The effective mass matrix of the light neutrinos is then given by

$$m_{\mathrm{LL}}^{\nu} = m_{\mathrm{LL}}^{\mathrm{I}} + m_{\mathrm{LL}}^{\mathrm{II}}\ , \quad \text{where} \quad m_{\mathrm{LL}}^{\mathrm{I}} = -v_{\mathrm{u}}^2\, Y_\nu\, M_{\mathrm{RR}}^{-1}\, Y_\nu^T \tag{1}$$

is the type I see-saw mass matrix. One motivation for considering the type II see-saw is that it allows to construct models for partially degenerate neutrinos in a natural way, e.g. via a type II upgrade [5], which is otherwise difficult to achieve in type I models. From a rather model independent viewpoint, the type II mass term can be considered as an additional contribution to the lowest dimensional effective neutrino mass operator.

In the literature, the most discussed case is where the type II contribution is realized via $\mathrm{SU}(2)_{\mathrm{L}}$-triplets. There are in general two possibilities to generate the baryon asymmetry: via the decay of the lightest right-handed neutrino ν_{R}^1 or via the decay of one or more $\mathrm{SU}(2)_{\mathrm{L}}$-triplets [6, 7, 8]. In the first case, there are additional one-loop diagrams where virtual triplets are running in the loop [6, 9, 10, 11]. Referring to the contributions to the decay asymmetries for ν_{R}^1 proportional to $m_{\mathrm{LL}}^{\mathrm{I}}$ as $\varepsilon_1^{\mathrm{I}}$ and to the ones proportional to $m_{\mathrm{LL}}^{\mathrm{II}}$ as $\varepsilon_1^{\mathrm{II}}$, either or both contributions can be important for generating the baryon asymmetry. In many studies of leptogenesis in left-right symmetric models, it has been assumed that $\varepsilon_1^{\mathrm{I}}$ dominates even if neutrino masses stem dominantly from $m_{\mathrm{LL}}^{\mathrm{II}}$ (see e.g. [12, 13, 14, 15]). The case where $\varepsilon_1^{\mathrm{II}}$ dominates over $\varepsilon_1^{\mathrm{I}}$ has recently been studied in [11, 16]. It has the interesting feature that unlike in the type I see-saw scenario, there is in general no upper bound on the absolute neutrino mass scale [17] from type II leptogenesis, as has been pointed out in [11].

In this work, we analyze the consequences of the neutrino mass scale for baryogenesis via the out-of-equilibrium decay of the lightest right-handed (s)neutrinos in type II see-saw models. First, we calculate the type II contributions to the decay asymmetries for minimal scenarios based on the Standard Model (SM) and on the Minimal Supersymmetric Standard Model (MSSM), where the additional direct mass term for the neutrinos stems from the induced vev of a triplet Higgs. The result for the supersymmetric case is new and we correct the previous result in the scenario based on the Standard Model. We then develop an effective approach to type II leptogenesis, assuming a gap between the mass M_{R1} of the lightest (s)neutrino and the masses of the heavier

particles involved in generating neutrino masses. Leptogenesis in this framework is approximately independent of the specific realization of the neutrino mass operator. The calculation of the decay asymmetries using the effective approach confirms our results for the triplet scenarios in the limit of heavy triplets. We subsequently derive a general upper bound on the decay asymmetry and find that it increases with the neutrino mass scale. It leads to a lower bound on the mass of the lightest right-handed neutrino, which is significantly below the type I bound for partially degenerate neutrinos. It is worth emphasizing that these results are in sharp contrast to the type I see-saw mechanism where an upper bound on the neutrino mass scale is predicted. Here we find no upper limit on the neutrino mass scale which may be increased arbitrarily. Indeed we find that the lower bound on the mass of the lightest right-handed neutrino decreases as the physical neutrino mass scale increases. This allows a lower reheat temperature, making thermal leptogenesis more consistent with the gravitino constraints in supersymmetric models [18, 19, 20, 21]).

2 Decay Asymmetries for Type II via Triplets

We now consider minimal type II models based on the SM and the MSSM, where the type II see-saw is realized via an additional heavy $\mathrm{SU}(2)_\mathrm{L}$-triplet. We focus on the case where the asymmetry is generated via the decay of the lightest right-handed (s)neutrinos and assume hierarchical masses of the right-handed (s)neutrinos and $M_\Delta \gg M_{\mathrm{R}1}$.

2.1 Minimal Type II See-Saw Scenarios

In the MSSM extended by chiral superfields $\hat{\nu}^{\mathrm{C}i}$ ($i \in \{1,2,3\}$), which contain the right-handed neutrinos ν^i_R and $\mathrm{SU}(2)_\mathrm{L}$-triplet Higgs superfields $\hat{\Delta}$ and $\hat{\bar{\Delta}}$ with weak hypercharge 1 and -1, respectively, the relevant parts of the superpotential are

$$\begin{aligned}
\mathcal{W}^{\mathrm{MSSM}}_{\nu^\mathrm{C}} &= (Y_\nu)_{fj} (\hat{L}^f \cdot \hat{H}_\mathrm{u})\, \hat{\nu}^{\mathrm{C}j} + \frac{1}{2} \hat{\nu}^{\mathrm{C}i} (M_{\mathrm{RR}})_{ij} \hat{\nu}^{\mathrm{C}j} \;, && \text{(2a)}\\
\mathcal{W}^{\mathrm{MSSM}}_{Y_\Delta} &= \frac{1}{2} (Y_\Delta)_{fg}\, \hat{L}^{Tf}\, i\tau_2\, \hat{\Delta}\, \hat{L}^g \;, && \text{(2b)}\\
\mathcal{W}^{\mathrm{MSSM}}_{\Delta,H} &= M_\Delta\, \mathrm{Tr}(\hat{\Delta}\, \hat{\bar{\Delta}}) + \lambda_\mathrm{u}\, \hat{H}^T_\mathrm{u}\, i\tau_2\, \hat{\bar{\Delta}}\, \hat{H}_\mathrm{u} + \lambda_\mathrm{d}\, \hat{H}^T_\mathrm{d}\, i\tau_2\, \hat{\Delta}\, \hat{H}_\mathrm{d} \;. && \text{(2c)}
\end{aligned}$$

The dot indicates the $\mathrm{SU}(2)_\mathrm{L}$-invariant product, $(\hat{L}^f \cdot \hat{H}_\mathrm{u}) := \hat{L}^f_a (i\tau_2)^{ab} (\hat{H}_\mathrm{u})_b$, with τ_A ($A \in \{1,2,3\}$) being the Pauli matrices. Superfields are marked by hats and we have written the $\mathrm{SU}(2)_\mathrm{L}$-triplets as traceless 2×2-matrices

$$\hat{\Delta} = \begin{pmatrix} \hat{\Delta}^+/\sqrt{2} & \hat{\Delta}^{++} \\ \hat{\Delta}^0 & -\hat{\Delta}^+/\sqrt{2} \end{pmatrix} \text{ and } \hat{\bar{\Delta}} = \begin{pmatrix} \hat{\bar{\Delta}}^+/\sqrt{2} & \hat{\bar{\Delta}}^{++} \\ \hat{\bar{\Delta}}^0 & -\hat{\bar{\Delta}}^+/\sqrt{2} \end{pmatrix} . \tag{3}$$

In the SM, we only consider one triplet scalar field Δ, using an analogous notation as in the extended MSSM. The corresponding terms of the Lagrangian are

$$\mathcal{L}^{\mathrm{SM}}_{\nu_{\mathrm{R}}} = -(Y_\nu)_{fj}(L^f \cdot H)\,\nu^j_{\mathrm{R}} - \frac{1}{2}\overline{\nu^i_{\mathrm{R}}}(M_{\mathrm{RR}})_{ij}\nu^{\mathrm{C}j}_{\mathrm{R}} \;+\; \text{h.c.}\,, \tag{4a}$$

$$\mathcal{L}^{\mathrm{SM}}_{Y_\Delta} = -\frac{1}{2}\,(Y_\Delta)_{fg}\,L^{T\,f}\,i\tau_2\,\Delta\,L^g \;+\; \text{h.c.}\,, \tag{4b}$$

$$\mathcal{L}^{\mathrm{SM}}_{\Delta,H} = -M^2_\Delta\,\mathrm{Tr}(\Delta^\dagger\Delta) - \Lambda_{\mathrm{u}}\,H^T\,i\tau_2\,\Delta^\dagger\,H \;+\; \text{h.c.}\,. \tag{4c}$$

At low energy in the SM and in the MSSM, the type I contribution to the neutrino mass matrix of the light neutrinos is approximately given by the see-saw formula of equation (1),

$$m^{\mathrm{I}}_{\mathrm{LL}} = -\,v^2_{\mathrm{u}}\,Y_\nu\,M^{-1}_{\mathrm{RR}}\,Y^T_\nu\;. \tag{5}$$

v_{u} is the vacuum expectation value (vev) of the neutral component of the Higgs doublet which couples to the right-handed neutrinos and the lepton doublets, i.e. $v_{\mathrm{u}} = \langle H^0_{\mathrm{u}}\rangle$ in the MSSM and $v_{\mathrm{u}} = \langle H^0\rangle$ in the SM. An induced see-saw suppressed vev $v_\Delta = \langle\Delta^0\rangle$ of the neutral component of the scalar field contained in $\hat{\Delta}$ gives a naturally small direct mass for the left-handed neutrinos. It can also be viewed as resulting from realizing the effective neutrino mass operator by integrating out the triplet below its mass threshold at M_Δ. The type II contribution to the effective neutrino mass matrix is given by

$$m^{\mathrm{II}}_{\mathrm{LL}} = (Y_\Delta v_\Delta)^*\;,\;\;\text{with}\;\; v^{\mathrm{SM}}_\Delta := v^2_{\mathrm{u}}\Lambda_{\mathrm{u}}M^{-2}_\Delta \;\;\text{and}\;\; v^{\mathrm{MSSM}}_\Delta := v^2_{\mathrm{u}}\lambda_{\mathrm{u}}M^{-1}_\Delta\;. \tag{6}$$

The complete neutrino mass matrix in the minimal type II scenarios based on the SM and on the MSSM is thus given from the above equations as

$$m^\nu_{\mathrm{LL}} = m^{\mathrm{I}}_{\mathrm{LL}} + m^{\mathrm{II}}_{\mathrm{LL}} = -v^2_{\mathrm{u}}\,Y_\nu\,M^{-1}_{\mathrm{RR}}\,Y^T_\nu + (Y_\Delta v_\Delta)^*\;. \tag{7}$$

2.2 Results for the Decay Asymmetries

In this subsection we calculate the relevant decay asymmetries diagrammatically. The asymmetry from the decay of the lightest right-handed neutrino into a lepton doublet and a Higgs is defined as

$$\varepsilon_1 := \frac{\Gamma_{\nu^1_{\mathrm{R}}L} - \Gamma_{\nu^1_{\mathrm{R}}\overline{L}}}{\Gamma_{\nu^1_{\mathrm{R}}L} + \Gamma_{\nu^1_{\mathrm{R}}\overline{L}}}\;, \tag{8}$$

with the decay rate $\Gamma_{\nu^1_{\mathrm{R}}L} := \sum_{a,b}\Gamma(\nu^1_{\mathrm{R}} \to L^f_a H_{\mathrm{u}b})$. In addition, in the supersymmetric case, we need the decay asymmetries

$$\widetilde{\varepsilon}_1 := \frac{\Gamma_{\nu^1_{\mathrm{R}}\widetilde{L}} - \Gamma_{\nu^1_{\mathrm{R}}\widetilde{L}^*}}{\Gamma_{\nu^1_{\mathrm{R}}\widetilde{L}} + \Gamma_{\nu^1_{\mathrm{R}}\widetilde{L}^*}}\;,\quad \varepsilon_{\widetilde{1}} := \frac{\Gamma_{\widetilde{\nu}^{1*}_{\mathrm{R}}L} - \Gamma_{\widetilde{\nu}^1_{\mathrm{R}}\overline{L}}}{\Gamma_{\widetilde{\nu}^{1*}_{\mathrm{R}}L} + \Gamma_{\widetilde{\nu}^1_{\mathrm{R}}\overline{L}}}\;,\quad \widetilde{\varepsilon}_{\widetilde{1}} := \frac{\Gamma_{\widetilde{\nu}^1_{\mathrm{R}}\widetilde{L}} - \Gamma_{\widetilde{\nu}^{1*}_{\mathrm{R}}\widetilde{L}^*}}{\Gamma_{\widetilde{\nu}^1_{\mathrm{R}}\widetilde{L}} + \Gamma_{\widetilde{\nu}^{1*}_{\mathrm{R}}\widetilde{L}^*}} \tag{9}$$

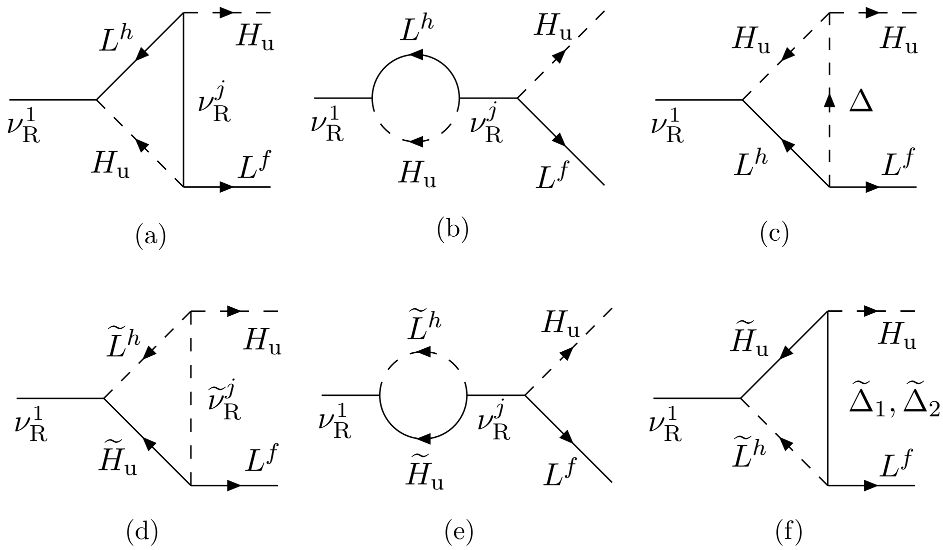

Figure 1: Loop diagrams in the MSSM which contribute to the decay $\nu_\mathrm{R}^1 \to L_a^f H_{\mathrm{u}b}$ for the case of a type II see-saw mechanism where the direct mass term for the neutrinos stems from the induced vev of a Higgs triplet. In diagram (f), $\widetilde{\Delta}_1$ and $\widetilde{\Delta}_2$ are the mass eigenstates corresponding to the superpartners of the $\mathrm{SU}(2)_\mathrm{L}$-triplet scalar fields Δ and $\bar{\Delta}$. The SM diagrams are the ones where no superpartners (marked by a tilde) are involved and where H_u is renamed to the SM Higgs.

for the decay of ν_R^1 into slepton and Higgsino and for the decays of the sneutrino $\widetilde{\nu}_\mathrm{R}^1$. At tree level, the decay rates are

$$\begin{aligned}\Gamma_{\nu_\mathrm{R}^1 L} + \Gamma_{\nu_\mathrm{R}^1 \overline{L}} = \Gamma_{\nu_\mathrm{R}^1 \widetilde{L}} + \Gamma_{\nu_\mathrm{R}^1 \widetilde{L}^*} &= \Gamma_{\widetilde{\nu}_\mathrm{R}^{1*} L} = \Gamma_{\widetilde{\nu}_\mathrm{R}^1 \overline{L}} = \Gamma_{\widetilde{\nu}_\mathrm{R}^1 \widetilde{L}} = \Gamma_{\widetilde{\nu}_\mathrm{R}^{1*} \widetilde{L}^*} \\ &= \frac{M_{\mathrm{R}1}}{8\pi} (Y_\nu^\dagger Y_\nu)_{11} \, . \end{aligned} \tag{10}$$

The contributions to the decay asymmetries arise from the interference of the diagrams for the tree-level decays with the loop diagrams. The one-loop diagrams for the decay $\nu_\mathrm{R}^1 \to L_a^f H_{\mathrm{u}b}$ are shown in figure 1. Compared to the supersymmetric type I see-saw case, there are additional diagrams contributing to $\varepsilon_1^\mathrm{MSSM}$, 1(c) and 1(f), which involve the triplet Higgs and its superpartner. The additional diagrams corresponding to the decay of ν_R^1 into slepton and Higgsino and to the decays of the sneutrino $\widetilde{\nu}_\mathrm{R}^1$ are not shown explicitly, but are included in the analysis.

Using FeynCalc [22], the calculation of the decay asymmetries corresponding to the diagrams 1(c) and 1(f) of figure 1 yields

$$\varepsilon_1^{(c)} = -\frac{3}{8\pi} \frac{M_{\mathrm{R}1}}{v_\mathrm{u}^2} \frac{\sum_{fg} \mathrm{Im}\left[(Y_\nu^*)_{f1} (Y_\nu^*)_{g1} (m_\mathrm{LL}^\mathrm{II})_{fg}\right]}{(Y_\nu^\dagger Y_\nu)_{11}} \, y \left[-1 + y \ln\left(\frac{y+1}{y}\right)\right], \tag{11a}$$

$$\varepsilon_1^{(f)} = -\frac{3}{8\pi} \frac{M_{\mathrm{R}1}}{v_\mathrm{u}^2} \frac{\sum_{fg} \mathrm{Im}\left[(Y_\nu^*)_{f1} (Y_\nu^*)_{g1} (m_\mathrm{LL}^\mathrm{II})_{fg}\right]}{(Y_\nu^\dagger Y_\nu)_{11}} \, y \left[1 - (1+y) \ln\left(\frac{y+1}{y}\right)\right]. \tag{11b}$$

We have defined $y := M_\Delta^2/M_{\mathrm{R1}}^2$. For dealing with lepton number violating interactions, we use the methods derived in [23]. The results for the contributions to the decay asymmetries from the triplet in the SM and from the triplet superfields in the MSSM are

$$\varepsilon_1^{\mathrm{SM,II}} = \varepsilon_1^{(c)} , \tag{12a}$$
$$\varepsilon_1^{\mathrm{MSSM,II}} = \varepsilon_1^{(c)} + \varepsilon_1^{(f)} . \tag{12b}$$

The MSSM results are new. In the SM, we correct the previous result of [11] by a factor of $-3/2$. As we will see below, our results in the limit $y \gg 1$ agree with the calculation in the effective approach, where the particles much heavier than M_{R1} are integrated out. In the MSSM, we furthermore obtain

$$\varepsilon_1^{\mathrm{MSSM,II}} = \widetilde{\varepsilon}_1^{\,\mathrm{MSSM,II}} = \varepsilon_{\widetilde{1}}^{\mathrm{MSSM,II}} = \widetilde{\varepsilon}_{\widetilde{1}}^{\,\mathrm{MSSM,II}} . \tag{13}$$

In addition, we reproduce the known results [24] for the decay asymmetries corresponding to the diagrams (a), (b), (d) and (e) which contribute to $\varepsilon_1^{\mathrm{I}}$ in the SM and in the MSSM:

$$\varepsilon_1^{(a)} = \frac{1}{8\pi}\frac{\sum_{j\neq 1}\mathrm{Im}\,[(Y_\nu^\dagger Y_\nu)^2_{1j}]}{\sum_f |(Y_\nu)_{f1}|^2}\sqrt{x_j}\left[1-(1+x_j)\ln\left(\frac{x_j+1}{x_j}\right)\right], \tag{14a}$$
$$\varepsilon_1^{(b)} = \frac{1}{8\pi}\frac{\sum_{j\neq 1}\mathrm{Im}\,[(Y_\nu^\dagger Y_\nu)^2_{1j}]}{\sum_f |(Y_\nu)_{f1}|^2}\sqrt{x_j}\left[\frac{1}{1-x_j}\right], \tag{14b}$$
$$\varepsilon_1^{(d)} = \frac{1}{8\pi}\frac{\sum_{j\neq 1}\mathrm{Im}\,[(Y_\nu^\dagger Y_\nu)^2_{1j}]}{\sum_f |(Y_\nu)_{f1}|^2}\sqrt{x_j}\left[-1+x_j\ln\left(\frac{x_j+1}{x_j}\right)\right], \tag{14c}$$
$$\varepsilon_1^{(e)} = \frac{1}{8\pi}\frac{\sum_{j\neq 1}\mathrm{Im}\,[(Y_\nu^\dagger Y_\nu)^2_{1j}]}{\sum_f |(Y_\nu)_{f1}|^2}\sqrt{x_j}\left[\frac{1}{1-x_j}\right], \tag{14d}$$

with $x_j := M_{\mathrm{R}j}^2/M_{\mathrm{R1}}^2$ for $j \neq 1$. The results for the type I contribution to the decay asymmetries in the SM and in the MSSM are

$$\varepsilon_1^{\mathrm{SM,I}} = \varepsilon_1^{(a)} + \varepsilon_1^{(b)} , \tag{15a}$$
$$\varepsilon_1^{\mathrm{MSSM,I}} = \varepsilon_1^{(a)} + \varepsilon_1^{(b)} + \varepsilon_1^{(d)} + \varepsilon_1^{(e)} . \tag{15b}$$

In the MSSM, the remaining decay asymmetries are equal to $\varepsilon_1^{\mathrm{MSSM,I}}$ [24],

$$\varepsilon_1^{\mathrm{MSSM,I}} = \widetilde{\varepsilon}_1^{\,\mathrm{MSSM,I}} = \varepsilon_{\widetilde{1}}^{\mathrm{MSSM,I}} = \widetilde{\varepsilon}_{\widetilde{1}}^{\,\mathrm{MSSM,I}} . \tag{16}$$

Note that the type I results can be brought to a form which contains the neutrino mass matrix using

$$\frac{1}{8\pi}\frac{\sum_{j\neq 1}\mathrm{Im}\,[(Y_\nu^\dagger Y_\nu)^2_{1j}]}{\sum_f |(Y_\nu)_{f1}|^2}\frac{1}{\sqrt{x_j}} = -\frac{1}{8\pi}\frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2}\frac{\sum_{fg}\mathrm{Im}\,[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^{\mathrm{I}})_{fg}]}{(Y_\nu^\dagger Y_\nu)_{11}} . \tag{17}$$

In the limit $y \gg 1$ and $x_j \gg 1$ for all $j \neq 1$, which corresponds to a large gap between the mass $M_{\mathrm{R}1}$ and the masses $M_{\mathrm{R}2}$, $M_{\mathrm{R}3}$ and M_Δ, using

$$z\left[1-(1+z)\ln\left(\frac{z+1}{z}\right)\right] \overset{z\gg 1}{\to} -\frac{1}{2}\,, \tag{18a}$$

$$z\left[\frac{1}{1-z}\right] \overset{z\gg 1}{\to} -1\,, \tag{18b}$$

$$z\left[-1+z\ln\left(\frac{z+1}{z}\right)\right] \overset{z\gg 1}{\to} -\frac{1}{2} \tag{18c}$$

for $z \in \{y, x_j\}$, we obtain the simple results for the decay asymmetries $\varepsilon_1^{\mathrm{SM}} = \varepsilon_1^{\mathrm{SM,I}} + \varepsilon_1^{\mathrm{SM,II}}$ and $\varepsilon_1^{\mathrm{MSSM}} = \varepsilon_1^{\mathrm{MSSM,I}} + \varepsilon_1^{\mathrm{MSSM,II}}$,

$$\varepsilon_1^{\mathrm{SM}} = \frac{3}{16\pi}\frac{M_{\mathrm{R}1}}{v_{\mathrm{u}}^2}\frac{\sum_{fg}\mathrm{Im}\left[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^{\mathrm{I}}+m_{\mathrm{LL}}^{\mathrm{II}})_{fg}\right]}{\sum_h |(Y_\nu)_{h1}|^2}\,, \tag{19a}$$

$$\varepsilon_1^{\mathrm{MSSM}} = \frac{3}{8\pi}\frac{M_{\mathrm{R}1}}{v_{\mathrm{u}}^2}\frac{\sum_{fg}\mathrm{Im}\left[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^{\mathrm{I}}+m_{\mathrm{LL}}^{\mathrm{II}})_{fg}\right]}{\sum_h |(Y_\nu)_{h1}|^2}\,. \tag{19b}$$

In the presence of such a mass gap, the calculation can also be performed in an effective approach after integrating out the two heavy right-handed neutrinos and the heavy triplet, generating contributions to the effective neutrino mass operator, as we now discuss.

3 Effective Approach to Type II Leptogenesis

In the SM and the MSSM, viewed as effective theories, neutrino masses can be introduced via the lowest dimensional effective neutrino mass operator

$$\mathscr{L}_\kappa^{\mathrm{SM}} = \frac{1}{4}\kappa_{gf}\,(\overline{L^{\mathrm{C}}}^g\cdot H)\;(L^f\cdot H) + \text{h.c.}\,, \tag{20a}$$

$$\mathscr{L}_\kappa^{\mathrm{MSSM}} = -\frac{1}{4}\kappa_{gf}\,(\hat{L}^g\cdot \hat{H}_{\mathrm{u}})\,(\hat{L}^f\cdot \hat{H}_{\mathrm{u}})\,\big|_{\theta\theta} + \text{h.c.}\,. \tag{20b}$$

After electroweak symmetry breaking, the effective operator yields Majorana masses for the light neutrinos,

$$\mathcal{L}_\nu = -\tfrac{1}{2}m^\nu_{LL}\overline{\nu}_{\mathrm{L}}\nu_{\mathrm{L}}^{\mathrm{C}f}\,, \quad \text{with} \quad m^\nu_{\mathrm{LL}} = -\frac{v_{\mathrm{u}}^2}{2}(\kappa)^*\,. \tag{21}$$

Let us assume that the lepton asymmetry is generated via the decay of the lightest right-handed neutrino and that all other additional particles, in particular the ones which generate the type II contribution, are much heavier than $M_{\mathrm{R}1}$. We furthermore assume that we can neglect their population in the early universe, e.g. that their masses

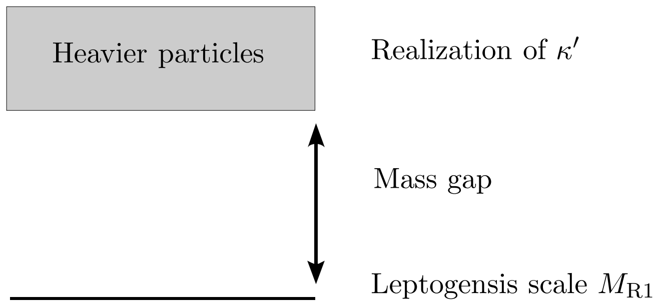

Figure 2: Graphical illustration of the effective description of neutrino masses at the leptogenesis scale.

are much larger than the reheating temperature T_R and that they are not produced non-thermally in a large amount. We also assume that they approximately do not contribute to washout processes. This scenario is motivated by supersymmetric GUTs, where additional charged particles like e.g. $\mathrm{SU}(2)_{\mathrm{L}}$-triplets with intermediate scale masses could spoil gauge coupling unification at $M_{\mathrm{GUT}} \approx 2 \cdot 10^{16}$ GeV.

For a minimal effective approach, it is convenient to isolate the type I contribution from the lightest right-handed neutrino as follows:

$$m^{\nu}_{\mathrm{LL}} \;=\; -\frac{v_{\mathrm{u}}^2}{2}\left[2(Y_\nu)_{f1} M_{\mathrm{R1}}^{-1} (Y_\nu^T)_{1f} + \kappa'^{*}\right] . \tag{22}$$

κ' includes type I contributions from the heavier right-handed neutrinos, plus any additional (type II) contributions from heavier particles. Examples for realizations of the neutrino mass operator can be found e.g. in [25]. At M_{R1}, the most minimal extension of the SM or the MSSM would then be to introduce the effective neutrino mass operator κ' plus one right-handed neutrino ν^1_{R} with mass M_{R1} and Yukawa couplings $(Y_\nu)_{f1}$ to the lepton doublets L^f, defined as $(Y_\nu)_{f1}(\hat{L}^f \cdot \hat{H}_{\mathrm{u}})\,\hat{\nu}^{\mathrm{C}1}$ in the superpotential of the MSSM and $-(Y_\nu)_{f1}(L^f \cdot H)\,\nu^1_{\mathrm{R}}$ in Lagrangian of the SM. The situation is illustrated in figure 2.

3.1 Decay Asymmetries for the SM and MSSM

The contributions to the decay asymmetries in the effective approach stem from the interference of the diagram for the tree-level decay with the loop diagrams containing the effective operator. In the SM, the interference with diagram (a) of figure 3 gives the simple result

$$\varepsilon_1^{\mathrm{SM}} = \frac{3}{16\pi}\frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2}\frac{\sum_{fg} \mathrm{Im}\left[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m^{\nu}_{\mathrm{LL}})_{fg}\right]}{(Y_\nu^\dagger Y_\nu)_{11}} =: -\frac{3}{16\pi}\frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2}\left\langle m^{\mathrm{BAU}}\right\rangle\;, \tag{23}$$

where we have introduced the effective mass for leptogenesis $\left\langle m^{\mathrm{BAU}}\right\rangle$,

$$\left\langle m^{\mathrm{BAU}}\right\rangle := -\frac{\sum_{fg} \mathrm{Im}\left[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m^{\nu}_{\mathrm{LL}})_{fg}\right]}{(Y_\nu^\dagger Y_\nu)_{11}}\;. \tag{24}$$

For the supersymmetric case, diagram (a) and diagram (b) contribute to ε_1 and we obtain:

$$\varepsilon_1^{\mathrm{MSSM}} = \frac{3}{8\pi}\frac{M_{\mathrm{R}1}}{v_{\mathrm{u}}^2}\frac{\sum_{fg}\mathrm{Im}\,[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^\nu)_{fg}]}{(Y_\nu^\dagger Y_\nu)_{11}} =: -\frac{3}{8\pi}\frac{M_{\mathrm{R}1}}{v_{\mathrm{u}}^2}\left\langle m^{\mathrm{BAU}}\right\rangle . \tag{25}$$

Explicit calculation furthermore yields

$$\varepsilon_1^{\mathrm{MSSM}} = \widetilde{\varepsilon}_1^{\,\mathrm{MSSM}} = \varepsilon_{\widetilde{1}}^{\mathrm{MSSM}} = \widetilde{\varepsilon}_{\widetilde{1}}^{\,\mathrm{MSSM}} . \tag{26}$$

The results are independent of the details of the realization of the neutrino mass operator κ'. Note that, since the diagrams where the lightest right-handed neutrino runs in the loop do not contribute to leptogenesis, we have written $m_{\mathrm{LL}}^\nu = -\frac{v_{\mathrm{u}}^2}{2}(\kappa)^*$ instead of $m'^{\nu}_{\mathrm{LL}} := -\frac{v_{\mathrm{u}}^2}{2}(\kappa')^*$ in the formulae (23) - (25). Having done this, the decay asymmetries are then seen to be directly related to the neutrino mass matrix m_{LL}^ν.

For neutrino masses via the type I see-saw mechanism, they are in agreement with the known results [24] (equation (14)) in the limit $M_{\mathrm{R}2}, M_{\mathrm{R}3} \gg M_{\mathrm{R}1}$. In the limit $M_\Delta \gg M_{\mathrm{R}1}$, the results obtained in the effective approach are also in agreement with our full theory calculation in the minimal type II scenarios with $\mathrm{SU}(2)_{\mathrm{L}}$-triplets in equation (11). In particular, we confirm the correction by the factor $-3/2$ compared to the previous result of [11] in the SM.

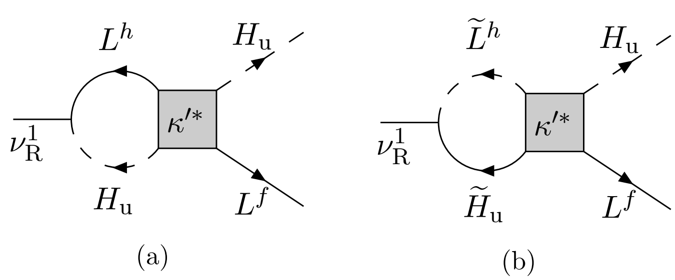

Figure 3: Loop diagrams contributing to the decay asymmetry via the decay $\nu_{\mathrm{R}}^1 \to L_a^f H_{\mathrm{u}b}$ in the MSSM with a (lightest) right-handed neutrino ν_{R}^1 and a neutrino mass matrix determined by κ'. Further contributions to the generated baryon asymmetry stem from the decay of ν_{R}^1 into slepton and Higgsino and from the decays of the sneutrino $\widetilde{\nu}_{\mathrm{R}}^1$. With H_{u} renamed to the SM Higgs, the first diagram contributes in the extended SM.

3.2 The Produced Baryon Asymmetry

The generated B-L asymmetry, i.e. the ratio of the number density over the entropy density $Y_{\mathrm{B-L}} = n_{\mathrm{B-L}}/s$, can be written as

$$Y_{\mathrm{B-L}}^{\mathrm{SM}} = -\eta\,\varepsilon_1\,Y_{\nu_{\mathrm{R}}^1}^{\mathrm{eq}} , \tag{27a}$$

$$Y_{\mathrm{B-L}}^{\mathrm{MSSM}} = -\eta\left[\tfrac{1}{2}(\varepsilon_1 + \widetilde{\varepsilon}_1)\,Y_{\nu_{\mathrm{R}}^1}^{\mathrm{eq}} + \tfrac{1}{2}(\varepsilon_{\widetilde{1}} + \widetilde{\varepsilon}_{\widetilde{1}})\,Y_{\widetilde{\nu}_{\mathrm{R}}^1}^{\mathrm{eq}}\right] . \tag{27b}$$

ε_1 (and $\widetilde{\varepsilon}_1$) are the decay asymmetries of the lightest right-handed neutrino into (s)lepton and Higgs(ino) and $\varepsilon_{\widetilde{1}}$ (and $\widetilde{\varepsilon}_{\widetilde{1}}$) are the decay asymmetries of the lightest right-handed sneutrino. Ignoring supersymmetry breaking, the right-handed neutrinos and sneutrinos have equal mass M_{R1}. $Y^{\mathrm{eq}}_{\nu^1_{\mathrm{R}}}$ and $Y^{\mathrm{eq}}_{\widetilde{\nu}^1_{\mathrm{R}}}$ are the number densities of the neutrino and sneutrino at $T \gg M_{\mathrm{R1}}$ if they were in thermal equilibrium, normalized with respect to the entropy density. They are given by

$$Y^{\mathrm{eq}}_{\nu^1_{\mathrm{R}}} \approx \frac{45\,\zeta(3)}{\pi^4 g_* k}\frac{3}{4} \;\text{ and }\; Y^{\mathrm{eq}}_{\widetilde{\nu}^1_{\mathrm{R}}} \approx \frac{45\,\zeta(3)}{\pi^4 g_* k}\;, \tag{28}$$

where g^* is the effective number of degrees of freedom, which amounts 106.75 in the SM and 228.75 in the MSSM, and k is the Boltzmann constant.

Equation (27) also provides the definition for the efficiency factor η for leptogenesis. It can be computed from a set of coupled Boltzmann equations (see e.g. [26]) and it is subject to e.g. thermal correction [27] and corrections from spectator processes [28], $\Delta\mathrm{L}=1$ processes involving gauge bosons [29, 27] and from renormalization group running [30, 31]. In the effective approach and for thermal leptogenesis with a reheating temperature $T_{\mathrm{R}} \gg M_{\mathrm{R1}}$, which is most independent of the cosmological model and of the model for neutrino masses, we assume that to a good approximation the efficiency factor depends only on the quantity $\widetilde{m}_1$ [26], defined by

$$\widetilde{m}_1 := \frac{\sum_f (Y^\dagger_\nu)_{1f}(Y_\nu)_{f1}\, v_{\mathrm{u}}^2}{M_{\mathrm{R1}}}\;, \tag{29}$$

and on the initial population of right-handed (s)neutrinos. This means, we neglect e.g. the contribution to washout processes from diagrams involving the additional particles which are involved in realizing the effective operator κ'. For example, in type I see-saw scenarios the effects from the heavier right-handed neutrinos and their Yukawa couplings can be neglected if M_{R1} is much smaller than 10^{14} GeV. Under this assumption, we can use the results for η from type I see-saw models. See e.g. [27] for figures showing $\eta(\widetilde{m}_1)$ for various initial populations of right-handed (s)neutrinos. A population of right-handed (s)neutrinos required for leptogenesis can also be produced non-thermally, e.g. via the decay of the inflaton. Such scenarios depend on the specific cosmological model. They could be very efficient, since ν^1_{R} and $\widetilde{\nu}^1_{\mathrm{R}}$ would be almost completely out-of-equilibrium when they decay.

From the decay of the right-handed (s)neutrinos, a lepton asymmetry is produced which is then transformed into a baryon asymmetry via sphaleron transitions. Since the latter conserve B-L, we write the negative of the lepton asymmetry as B-L asymmetry in equation (27). The baryon asymmetry is then related to the B-L asymmetry Y_{B} via

$$Y_{\mathrm{B}} = \alpha\, Y_{\mathrm{B-L}}\;, \;\text{ with }\; \alpha \approx \frac{24+4N_H}{66+13N_H} \tag{30}$$

and with N_H being the number of Higgs doublets. With $\varepsilon_1 = \widetilde{\varepsilon}_1 = \varepsilon_{\widetilde{1}} = \widetilde{\varepsilon}_{\widetilde{1}}$ from equation (26) in the MSSM and using $s/n_\gamma \approx 7.04k$, the produced baryon asymmetry in terms of the baryon to photon ratio in the SM and in the MSSM is approximately given by

$$\frac{n_{\mathrm{B}}^{\mathrm{SM}}}{n_\gamma} \approx -0.97 \cdot 10^{-2}\, \varepsilon_1\, \eta\,, \tag{31a}$$

$$\frac{n_{\mathrm{B}}^{\mathrm{MSSM}}}{n_\gamma} \approx -1.04 \cdot 10^{-2}\, \varepsilon_1\, \eta\,. \tag{31b}$$

Note that the sign of the produced asymmetry is a relevant quantity here. n_{B} has to be positive since we calculate in the convention that we consist of matter and not of anti-matter. In terms of the effective mass for leptogenesis, defined in equation (24), $\left\langle m^{\mathrm{BAU}} \right\rangle > 0$ is required for obtaining $n_{\mathrm{B}} > 0$.

4 Type II Bound on Decay Asymmetry and on M_{R1}

In the effective approach, we can calculate a model-independent upper bound for the decay asymmetries $\varepsilon_1^{\mathrm{SM}}$ and $\varepsilon_1^{\mathrm{MSSM}}$ from the requirement of successful thermal leptogenesis. For obtaining this bound, it is useful to choose a basis where m_{LL}^ν (and M_{RR}) are diagonal. Note that the decay asymmetry is independent of the basis for Y_e . In this basis, we can write

$$(Y_\nu)_{1f} = \begin{pmatrix} \widetilde{y}_{11}\, e^{\mathrm{i}\phi_1} \\ \widetilde{y}_{21}\, e^{\mathrm{i}\phi_2} \\ \widetilde{y}_{31}\, e^{\mathrm{i}\phi_3} \end{pmatrix}, \quad m_{\mathrm{LL}}^\nu = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}, \tag{32}$$

with real and positive $\widetilde{y}_{11}, \widetilde{y}_{12}$ and $\widetilde{y}_{13}$. For the effective mass for leptogenesis $\left\langle m^{\mathrm{BAU}} \right\rangle$, defined in equation (24), we obtain

$$\begin{aligned} \left\langle m^{\mathrm{BAU}} \right\rangle &= -\frac{\sum_{fg} \mathrm{Im}\left[(Y_\nu^*)_{f1}(Y_\nu^*)_{g1}(m_{\mathrm{LL}}^\nu)_{fg}\right]}{(Y_\nu^\dagger Y_\nu)_{11}} \leq \frac{\widetilde{y}_{11}^2 m_1 + \widetilde{y}_{21}^2 m_2 + \widetilde{y}_{31}^2 m_3}{\widetilde{y}_{11}^2 + \widetilde{y}_{21}^2 + \widetilde{y}_{31}^2} \\ &\leq m_{\max}^\nu\,, \end{aligned} \tag{33}$$

with $m_{\max}^\nu := \max(m_1, m_2, m_3)$ being the largest neutrino mass at the energy scale M_{R1}. Using equation (23) and equation (25), this leads to the upper bounds

$$|\varepsilon_1^{\mathrm{SM}}| \leq \frac{3}{16\pi} \frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} m_{\max}^\nu\,, \tag{34a}$$

$$|\varepsilon_1^{\mathrm{MSSM}}| \leq \frac{3}{8\pi} \frac{M_{\mathrm{R1}}}{v_{\mathrm{u}}^2} m_{\max}^\nu \tag{34b}$$

for the decay asymmetries. Thus, the upper bound increases with increasing mass scale of the light neutrinos. Note that compared to the low energy value, the neutrino masses

at the scale $M_{\rm R1}$ are enlarged by renormalization group (RG) effects by $\approx +20\%$ in the MSSM and $\approx +30\%$ in the SM, which raises the bounds on the decay asymmetries by the same values. More accurate results can be found e.g. in figure 4 of [31].

Using equation (31), for a given efficiency factor η and using an upper bound for $m^\nu_{\rm max}$, it can be transformed into a lower type II bound for the mass of the lightest right-handed neutrino:

$$M_{\rm R1}^{\rm SM} \geq \frac{16\pi}{3}\frac{v_{\rm u}^2}{m^\nu_{\rm max}}\frac{n_{\rm B}/n_\gamma}{0.97\cdot 10^{-2}\,\eta}\,, \tag{35a}$$

$$M_{\rm R1}^{\rm MSSM} \geq \frac{8\pi}{3}\frac{v_{\rm u}^2}{m^\nu_{\rm max}}\frac{n_{\rm B}/n_\gamma}{1.04\cdot 10^{-2}\,\eta}\,. \tag{35b}$$

The bound on $M_{\rm R1}$ is lower for a larger neutrino mass scale. It is shown in figure 4 as a function of the neutrino mass scale, i.e. of the mass of the lightest neutrino.

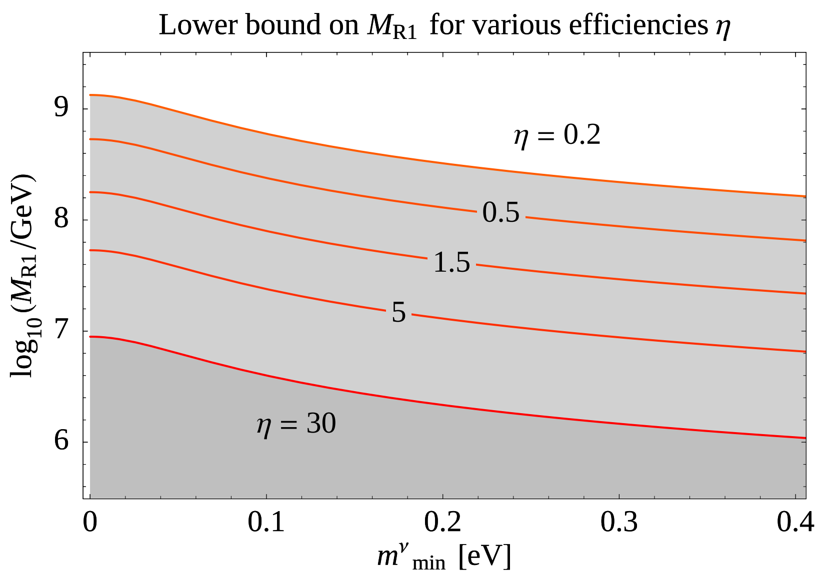

Figure 4: Graphical illustration of the lower bound on $M_{\rm R1}$ in the MSSM as a function of the mass of the lightest neutrino $m^\nu_{\rm min} := \min(m_1, m_2, m_3)$ for some values of the efficiency factor η and for a baryon to photon ratio $n_B = 6.5\cdot 10^{-10}$. In the extreme cases for thermal leptogenesis, the maximal value of the efficiency factor is $\eta^{\rm zero}_{\rm max} \approx 0.2$ for a zero initial population of $\nu_{\rm R1}$ and $\eta^{\rm dom.}_{\rm max} \approx 30$ for a maximal initial population (approximate values taken from [27]). RG corrections to the neutrino masses at the scale $M_{\rm R1}$ of $\approx +20\%$ in the MSSM and $\approx +30\%$ in the SM are included (see e.g. figure 4 in [31]).

The situation in the type II framework is very different to the type I see-saw case: E.g., for a normal mass ordering, the type II bound on the decay asymmetry is proportional to m_3, whereas the type I bound is proportional to $\Delta m^2_{31}/m_3$. In addition, thermal type I leptogenesis gets less efficient for a larger neutrino mass scale since $\widetilde{m}_1 \geq m^\nu_{\rm min}$,

with $m^\nu_{\mathrm{min}} := \min(m_1, m_2, m_3)$. Together with an improved bound [17] on the type I decay asymmetry, this strongly increases the type I bound on $M_{\mathrm{R}1}$ [32] for increasing m^ν_{min} and finally leads to an upper bound for the absolute mass scale of the light neutrinos of $m^\nu_{\mathrm{min}} \leq 0.12$ eV [33]. In the type II scenario where $\widetilde{m}_1$ is in general independent of m^ν_{max}, there is no bound on the neutrino mass scale from the requirement of successful leptogenesis. A neutrino mass scale $\lesssim 0.35$ eV on the contrary allows for a mass of the lightest right-handed neutrino of about an order of magnitude below the bound in type I models, which might help thermal leptogenesis with respect to the gravitino problem in supersymmetric models. Note that in non-thermal leptogenesis scenarios, a lower bound on $M_{\mathrm{R}1}$ does in general not lead to a conflict with respect to the gravitino problem.

5 Summary and Conclusions

In this work, we have investigated type II leptogenesis via the decay of the lightest (s)neutrinos. In the MSSM with the type II contribution realized via an additional $\mathrm{SU}(2)_{\mathrm{L}}$-triplet superfield, we have calculated the decay asymmetries for the lightest right-handed neutrino ν^1_{R} and its superpartner $\widetilde{\nu}^1_{\mathrm{R}}$. In the SM, we have recalculated the decay asymmetry $\varepsilon^{\mathrm{II}}_1$ and corrected the previous result. We have developed an effective approach, assuming a gap between the mass $M_{\mathrm{R}1}$ of the lightest (s)neutrino and the masses of the remaining particles involved in generating the neutrino masses. We have calculated the effective decay asymmetries in the SM and in the MSSM. Leptogenesis in this framework is independent of the specific realization of the neutrino mass operator. The total decay asymmetry ε_1 is proportional to the complete neutrino mass matrix $m^\nu_{\mathrm{LL}} = m^{\mathrm{I}}_{\mathrm{LL}} + m^{\mathrm{II}}_{\mathrm{LL}}$. We have derived a general upper bound (equation (34)) on the total decay asymmetry and found that it increases with the neutrino mass scale, in sharp contrast to the type I case which leads to an upper bound of about 0.1 eV on the neutrino mass scale. It leads to a lower bound (equation (35) and figure 4) on the mass of the lightest right-handed neutrino significantly below the type I bound for partially degenerate neutrinos. Increasing the neutrino mass scale allows a lower reheat temperature, making thermal type II leptogenesis more consistent with the gravitino constraints in supersymmetric models.

Acknowledgements

We would like to thank Michael Ratz for useful discussions. We acknowledge support from the PPARC grant PPA/G/O/2002/00468.

References

[1] M. Fukugita and T. Yanagida, *Baryogenesis without grand unification*, Phys. Lett. **174B** (1986), 45.

[2] D. N. Spergel et al., *First year Wilkinson Microwave Anisotropy Probe (WMAP) observations: Determination of cosmological parameters*, (2003), `astro-ph/0302209`.

[3] T. Yanagida in *Proc. of the Workshop on Unified Theory and Baryon Number of the Universe*, KEK, Japan, 1979; S.L. Glashow, Cargese Lectures (1979); M. Gell-Mann, P. Ramond and R. Slansky in Sanibel Talk, CALT-68-709, Feb 1979, and in *Supergravity* (North Holland, Amsterdam 1979); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44** (1980) 912.

[4] M. Magg and C. Wetterich, Phys. Lett. B **94** (1980) 61; G. Lazarides, Q. Shafi and C. Wetterich, Nucl. Phys. B **181** (1981) 287; R. N. Mohapatra and G. Senjanović, Phys. Rev. **D23** (1981), 165; C. Wetterich, Nucl. Phys. **B187** (1981), 343.

[5] S. Antusch and S. F. King, *From hierarchical to partially degenerate neutrinos via type II upgrade of type I see-saw models*, (2004), `hep-ph/0402121`.

[6] P. J. O'Donnell and U. Sarkar, *Baryogenesis via lepton number violating scalar interactions*, Phys. Rev. **D49** (1994), 2118–2121, `hep-ph/9307279`.

[7] E. Ma and U. Sarkar, *Neutrino masses and leptogenesis with heavy Higgs triplets*, Phys. Rev. Lett. **80** (1998), 5716–5719, `hep-ph/9802445`.

[8] T. Hambye, E. Ma, and U. Sarkar, *Supersymmetric triplet Higgs model of neutrino masses and leptogenesis*, Nucl. Phys. **B602** (2001), 23–38, `hep-ph/0011192`.

[9] G. Lazarides and Q. Shafi, *R symmetry in MSSM and beyond with several consequences*, Phys. Rev. **D58** (1998), 071702, `hep-ph/9803397`.

[10] E. J. Chun and S. K. Kang, *Baryogenesis and degenerate neutrinos*, Phys. Rev. D **63** (2001) 097902, `hep-ph/0001296`.

[11] T. Hambye and G. Senjanovic, *Consequences of triplet seesaw for leptogenesis*, (2003), `hep-ph/0307237`.

[12] A. S. Joshipura and E. A. Paschos, *Constraining leptogenesis from laboratory experiments*, (1999), `hep-ph/9906498`.

[13] A. S. Joshipura, E. A. Paschos, and W. Rodejohann, *Leptogenesis in left-right symmetric theories*, Nucl. Phys. **B611** (2001), 227–238, `hep-ph/0104228`.

[14] A. S. Joshipura, E. A. Paschos, and W. Rodejohann, *A simple connection between neutrino oscillation and leptogenesis*, JHEP **08** (2001), 029, `hep-ph/0105175`.

[15] W. Rodejohann, *Leptogenesis, mass hierarchies and low energy parameters*, Phys. Lett. **B542** (2002), 100–110, `hep-ph/0207053`.

[16] W. Rodejohann, *Type II see-saw mechanism, deviations from bimaximal neutrino mixing and leptogenesis*, `hep-ph/0403236`.

[17] W. Buchmüller, P. Di Bari, and M. Plümacher, *The neutrino mass window for baryogenesis*, Nucl. Phys. **B665** (2003), 445–468, `hep-ph/0302092`.

[18] M. Y. Khlopov and A. D. Linde, *Is it easy to save the gravitino?*, Phys. Lett. **B138** (1984), 265–268.

[19] J. R. Ellis, J. E. Kim, and D. V. Nanopoulos, *Cosmological gravitino regeneration and decay*, Phys. Lett. **B145** (1984), 181.

[20] J. R. Ellis, D. V. Nanopoulos, and S. Sarkar, *The cosmology of decaying gravitinos*, Nucl. Phys. **B259** (1985), 175.

[21] T. Moroi, H. Murayama, and M. Yamaguchi, *Cosmological constraints on the light stable gravitino*, Phys. Lett. **B303** (1993), 289–294.

[22] R. Mertig, M. Böhm, and A. Denner, *FEYN CALC: Computer algebraic calculation of Feynman amplitudes*, Comput. Phys. Commun. **64** (1991), 345–359.

[23] A. Denner, H. Eck, O. Hahn, and J. Küblbeck, *Feynman rules for fermion number violating interactions*, Nucl. Phys. **B387** (1992), 467–484.

[24] L. Covi, E. Roulet, and F. Vissani, *CP violating decays in leptogenesis scenarios*, Phys. Lett. **B384** (1996), 169–174, `hep-ph/9605319`.

[25] E. Ma, *Pathways to naturally small neutrino masses*, Phys. Rev. Lett. **81** (1998), 1171–1174, `hep-ph/9805219`.

[26] W. Buchmuller and M. Plumacher, *Neutrino masses and the baryon asymmetry*, Int. J. Mod. Phys. **A15** (2000), 5047–5086, `hep-ph/0007176`.

[27] G. F. Giudice, A. Notari, M. Raidal, A. Riotto, and A. Strumia, *Towards a complete theory of thermal leptogenesis in the SM and MSSM*, (2003), `hep-ph/0310123`.

[28] W. Buchmüller and M. Plümacher, *Spectator processes and baryogenesis*, Phys. Lett. **B511** (2001), 74–76, `hep-ph/0104189`.

[29] A. Pilaftsis and T. E. J. Underwood, *Resonant leptogenesis*, `hep-ph/0309342`.

[30] R. Barbieri, P. Creminelli, A. Strumia, and N. Tetradis, *Baryogenesis through leptogenesis*, Nucl. Phys. **B575** (2000), 61–77, `hep-ph/9911315`.

[31] S. Antusch, J. Kersten, M. Lindner, and M. Ratz, *Running neutrino masses, mixings and CP phases: Analytical results and phenomenological consequences*, Nucl. Phys. **B674** (2003), 401–433, `hep-ph/0305273`.

[32] S. Davidson and A. Ibarra, *A lower bound on the right-handed neutrino mass from leptogenesis*, Phys. Lett. **B535** (2002), 25–32, `hep-ph/0202239`.

[33] W. Buchmüller, P. Di Bari, and M. Plümacher, *Leptogenesis for pedestrians*, (2004), `hep-ph/0401240`.